Analysis of the microstructured eutectic Tb$_3$Sc$_2$Al$_3$O$_{12}$-TbScO$_3$ photonic crystal properties

Agnieszka Mossakowska-Wyszyńska,$^{1,*}$ Marcin Kaczkan,$^{1}$ Marcin Koba,$^{2,3}$ Dorota Anna Pawlak,$^{4}$ Katarzyna Kołodziejak,$^{4}$ and Sebastian Turczyński$^{2}$

$^1$Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, Poland
$^2$Institute of Experimental Physics, University of Warsaw, Hoza 69, 00-681 Warsaw, Poland
$^3$National Institute of Telecommunications, Szachowa 1, 04-894 Warsaw, Poland
$^4$Institute of Electronic Materials Technology, Wólczynska 133, 00-667 Warsaw, Poland

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Abstract—In this paper, a numerical analysis of self-organized microstructured dielectric eutectic photonic crystal properties is presented. In particular, we study the terbium-scandium-aluminum garnet - terbium-scandium perovskite structure Tb$_3$Sc$_2$Al$_3$O$_{12}$-TbScO$_3$, grown by the micro-pulling down method. The self-organized dielectric microstructure is made of perovskite fibers embedded in a garnet phase matrix. In general, we analyzed the distribution of the electromagnetic field in the investigated periodic structures and the existence of a photonic band gap of such photonic crystals as a function of eutectic geometric parameters. Investigated structures do not reveal a wide photonic band gap, because of the low contrast of the refractive indices of individual phases.

In recent years, rapid development of theoretical and experimental research on photonic crystals [1] and metamaterials [2] is observed. In the case of photonic crystals, when the wavelength of light is comparable with a period of the photonic crystal periodic structure, this structure exhibits a photonic band gap. In metamaterials, on the other hand, the wavelength should be much bigger than the structuring of the material since only the effective properties such as effective permittivity and permeability are important.

In this paper, we present an analysis of photonic properties of dielectric eutectic Tb$_3$Sc$_2$Al$_3$O$_{12}$-TbScO$_3$ (TSAG-TSP) terbium-scandium-aluminum garnet - terbium-scandium perovskite. The investigated structure, presented in Fig. 1, was obtained by self-organization during growth by the micro-pulling down method [3]. The eutectic is characterized by the formation of two unmixable crystals from a completely mixable melt. The most interesting eutectic crystals point of view, would be the microstructures with regular shapes, i.e., lamellar and rodlike shapes. To show how photonic properties change with eutectic geometric parameters, we analyze TSAG-TSP samples with three different pulling rates. The diameter of the microrods decreases with increasing the pulling rate [4].

![Fig. 1. SEM picture of self-organized pseudo-hexagonally packed TSAG-TSP eutectic microstructure: cross-section (the perovskite phase is gray and the garnet phase is black). The structure is modelled by perfect hexagonal lattice with dimensions r~radius and a~period.](http://www.photonics.pl/PLP)

All the geometric parameters for each eutectic were calculated from SEM micrographs and then average parameters were obtained. These average parameters are shown in Table 1 for three different samples (Sample no.), where p.r. is the crystal pulling rate, 2r is the rod diameter in two perpendicular directions (hor.-horizontal, ver.-vertical, and aver.-averaged value), a is the period - average distance between rods, and r/a is the normalized ratio of average rod radius and crystal period. The investigated structure was modelled by perfect hexagonal lattice described by average rod radius $r$ and crystal period $a$.

Table 1. Eutectic geometric parameters calculated from micrographs for three samples. Abbreviations are explained in main text.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>p.r. [mm/min]</th>
<th>2r [μm]</th>
<th>aver</th>
<th>aver</th>
<th>a [μm]</th>
<th>r/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
<td>3.08</td>
<td>3.56</td>
<td>3.14</td>
<td>4.81</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>0.45</td>
<td>1.74</td>
<td>1.74</td>
<td>1.74</td>
<td>2.90</td>
<td>0.30</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>1.28</td>
<td>1.18</td>
<td>2.41</td>
<td>0.24</td>
<td></td>
</tr>
</tbody>
</table>

In order to increase the contrast of the eutectic crystals refractive index, the investigated structures have been subjected to selective chemical etching. In this process,

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* E-mail: A.Mossakowska@elka.pw.edu.pl

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two microstructures were obtained with a height/depth of rod/hole of about 1 μm, and were located on eutectic TSAG-TSP [3].

To perform numerical analysis of self-organized microstructure eutectic, we use refractive indices obtained by using a spectroscopic ellipsometer UVISEL, Jobin Yvon in the range from 0.6 to 6.5 eV (190-2100 nm), and Bruker FTIR spectrometer in the spectral range 7500-550 cm⁻¹ [5]. Optical functions were obtained by fitting the data with a model dielectric function fulfilling the Kramers-Kronig dispersion relations [5].

To find the optical properties of self-organized eutectic microstructures, we used free software (MIT Photonic Bands, MPB) with implemented Plane Wave Expansion Method PWEM [6, 7]. In addition, we assumed an infinite two-dimensional photonic structure with hexagonal lattice, which allowed us to use periodic boundary conditions. The rods and background material were homogenous in the perpendicular direction. This method allowed us to determine photonic crystal dispersion characteristics and analyze the photonic properties of investigated structures.

During numerical analysis, we calculated dispersion characteristics for the following eutectic structures: TSAG-TSP, TSAG-air and air-TSP of the three samples mentioned in Table 1. We made a series of numerical simulations which showed what should be the minimum of the refractive index of one eutectic phase for a constant refractive index of the second eutectic phase to have a photonic band gap of the investigated structure. We drew a lot of characteristics for different waveguide indices and a wide range of wavelengths for two kind of modes TE and TM.

All interesting results are summarized in Tables 2-4, where parameters for dispersion characteristics are shown. In Tables 2-4 we put: numerical calculation test number indicated in Tables column as No.; three kinds of eutectic structures: TSAG-TSP, TSAG-air, air-TSP; refraction indices n₁ for eutectic warp and n₂ for eutectic rods, photonic bad gap PBG in percent calculated from frequency relation [2(νₘₐₓ−νₘᵦ)/(νₘₐₓ+νₘᵦ)]×100%, the kind of mode and the wavelength range for the existing photonic band gap. Each numerical calculation test was performed for different eutectic structure and different refraction indices as indicated in Tables 2-4.

As we can see in Tables 2-4, photonic band gaps occur rather for TM mode and are very narrow, because the percent value of PBG is very low. All numerical simulations have some precision. In the used PWEM method, the obtained results of PBG at a level of 1% are on the border of error [6, 7]. Therefore we can say that in
Because of the limited volume of this paper, we show only three characteristics for investigated samples (as indicated in Table 1). In Figs. 2-4 we show dispersion characteristics for TM and TE modes. All Figures are plotted as a function of reciprocal lattice vector \( k \). On the vertical axis is the normalized frequency expressed as dependence of \( (\omega a/2\pi c) \), where \( \omega \) is the frequency and \( c \) is the velocity of light in free space.

In Fig. 2 we show the dispersion characteristics for eutectic structure sample 1 (Sample No. 1 Table 1) TSAG-TSP test 2 (No.2 Table 2), for which refraction indices are \( n_2=1.79 \) for eutectic warp and \( n_2=1.94 \) for eutectic rods. As we can see, the dispersion characteristics for two modes TE and TM overlap and for all normalized frequency the wave equation has a solution. Therefore, this eutectic structure has no photonic band gap.

In Fig. 4 we show the dispersion characteristics for eutectic structure sample 2 (Sample No. 2 Table 1) TSAG-air test 3 (No.3 Table 3), for \( n_2=1.79 \), \( n_2=1.00 \). In contrast to Fig. 3, here a photonic band gap appears only for TE mode and is located between the first and second bandwidth in a normalized frequency range from 0.516 to 0.523. Similarly as in Fig. 3, a photonic band gap appears in particular M direction of the reciprocal lattice.

In conclusion, we have demonstrated numerical analysis of photonic properties of self-organized dielectric eutectic microstructures. In investigated structures it is very hard to observe a photonic band gap, because of too low contrast of the refractive indices of individual phases. Moreover, a microstructured eutectic does not reveal a photonic band gap simultaneously for TE and TM waveguide modes.

**References**